Carbon-14 Plant Evidence of mid-Holocene Quelccaya Ice Cap Margin Fluctuations

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ABSTRACT

The North Lake Lobe of the Quelccaya Ice Cap in southern Peru represents a wholly unique location for reconstructing paleoclimate conditions. At this location, plant samples were preserved *in-situ* beneath the advancing glacial ice, and since 2004 have been collected as the ice retreats. The ages of the collected samples were obtained through radiocarbon dating methods. Samples were collected at the surface and at depth. The fine-grained nature of the matrix surrounding the preserved buried samples indicates that several flood events occurred at these sites between ~6,630 cal yr BP and ~6450 cal yr BP due to the ice damming of a lake above the sites. The temporal relationships of the samples were analyzed using a density kernel derivative function, and several groups of significantly related surface samples were determined. We were then able to map several successive advancing ice margins from ~6431 cal yr BP to ~4565 cal yr BP using the temporospatial data of the different sample groups. Comparing the findings of the advancing ice margins to regional climatic records, we determined that the principal driver of the Quelccaya Ice Cap behavior is temperature change, rather than changes in precipitation. Therefore, the advancement seen at the North Lake Lobe of the Quelccaya Ice Cap is another indicator of cooling regional temperatures in South America during the mid-Holocene. When compared to extensive temperature records from locations around the world, the North Lake Lobe advancement supports the hypothesis that a global cooling event occurred during the mid-Holocene.

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INTRODUCTION

To understand the variability of the modern climate, it is crucial to understand the climatic fluctuations of the Holocene. Considering that anthropogenic greenhouse gas emissions very likely caused much of the observed global warming in the last 50 years, we believe that understanding the Holocene is even more critical to determine the future impact of climate change as well as its severity in the context of past events (Hegerl et al., 2007). The North Lake Lobe of the Quelccaya Ice Cap (QIC) provides a unique record of remarkably well-preserved *in-situ* plant deposits along the recently deglaciated ice margins (Buffen et al., 2009). Well-preserved plant samples that are exposed by modern glacier retreat provide strong evidence of continuous ice coverage at their location since the encapsulation of the plant by the advancing ice (Anderson et al., 2008). Due to this continuous ice coverage, the calculated age of the plant samples correlate to the age of their preservation. Using these preserved *in-situ* plant samples, we constructed a ^{14}C chronology of advancement of the North Lake Lobe of the Quelccaya Ice Cap in southeastern Peru and then compare this to the regional ice core record extracted from the glacier on Huascarán in northern Peru. We then compare this North Lake Lobe ice margin record to other global temperature records from the mid-Holocene.

GEOLOGIC SETTING

Geography

The Peruvian/Bolivian Altiplano is located in the mountainous, western region of South America, between ~14°S and 22°S and 65°W and 69°W. With an average elevation of ~4000 m above sea level (masl) and an area of ~200,000 km^2, it is one of the highest plateaus in the world, second only to the Tibetan Plateau (Wirrman and de Oliveira Almeida, 1987). The North Lake Lobe is a large lobe of the QIC that is located on the western margin. Plant samples were collected from the surface and within banks of fine-grained sediment along the margins of the proglacial lake that exists at the edge of this lobe and of the ice itself.

Climate

The QIC experiences seasonal precipitation cycles, with most precipitation falling during the wet season between December and February (Aceituno, 1988; Garreaud et al., 2003). This moisture is supplied by the Atlantic Ocean, and is carried over the Amazon Basin by northeasterly trade winds before it is deposited over the Altiplano (Taljaard, 1972; Salati et al., 1979; Grootes et al., 1989). Due to the sharp topography along the western margin of the Altiplano, in combination with an atmospheric temperature inversion at ~800 masl, eastward movement of moisture from the Pacific is strongly inhibited (Rutllant and Ulriksen, 1979).

Geology

The QIC sits atop an ignimbrite plateau (Mercer and Palacios, 1977), and is very well suited as an area to study climate change due to its topography. The flat nature of the QIC means that changes in the mean elevation of the 0° isotherm affect large areas of the ice cap. (Buffen et al., 2009).

METHODS

Sample Collection

Vegetation samples were collected from their *in-situ* locations by members of the Ice Core Paleoclimatology Research Group at Ohio State. The uppermost portion of each vegetation sample was collected for dating purposes to obtain the most recent material from each deposit. Samples were collected by the following members of the Ice Core Paleoclimatology Group: L. Thompson, A. Buffen, M. Davis, N. Kehrwald, F. Vicencio, K. Mountain, R. Sierra, D. Kenny, Stacy Porter, S. Kutuzov. To avoid contamination by modern carbon, rubber gloves were worn during collection. Samples were collected within a year of their exposure, minimizing degradation and chance of contamination. There was no influx of natural carbon through biological means as there was no modern vegetation observed on any samples. There is also no influx of carbon from soils or peats, as the bedrock at the North Lake Lobe site is ignimbrite (Mercer and Palacios, 1977). Material was harvested from vegetation both at the surface and at depth. Subsurface vegetation was vertically sampled from layers of sediment deposits around the north rim of the lake. Sample depths were then measured with respect to the surface of the deposit. GPS coordinates of the plant location were recorded as degree decimal minutes, and later converted to decimal degrees using the Polar Geospatial Center's online conversion tool. Several samples were recovered during the 2004 field season, and then analyzed by Aron Buffen as part of his thesis research (Buffen et al., 2009).

Radiocarbon Dating

Samples were dated using AMS radiocarbon techniques at both the Woods Hole Oceanographic Institution's National Ocean Science Accelerator Mass Spectrometry Facility (NOSAMS) and the Center for Accelerator Mass Spectrometry (CAMS) at the Lawrence Livermore National Laboratory. If a sample possessed sufficient material, it was dated multiple times at one or both facilities. The ^{14}C dates were calibrated using the Calib 5.0.1 radiocarbon calibration program with the Southern Hemisphere dataset SHCal04 (Stuvier and Reimer, 1993; McCormac et al., 2004). Composite ages were calculated for samples from the North Lake using the 'C_Combine' function of the OxCal4 'R_Combine' function and weighted as a single sample in the composite site average (Bronk Ramsey, 1995; McCormac et al., 2004). Samples with multiple calculated age values were averaged.

Data Interpretation

Samples were correlated by calculated age and broken into temporally-related groups using the Derivatives of Kernel Density Estimator (dkde) function from the Kedd Library of the CRAN R system for statistical computation (see dkde section of the Appendices). The dkde function was used to estimate the first derivative of the probability density function (PDF) for the data distribution and the local minima of the PDF were determined from the relevant zeroes of the first derivative estimate. These minima can be used to determine breaks between groups of correlated data, as they are the points of lowest probability of a data point occurrence. The mean age and standard deviation of the samples in each class were calculated using the STDEV.P function of Microsoft Excel.

Mapping

Samples were displayed in ArcMap overlying satellite imagery that was acquired from TerraServer. This image was corrected using a third order polynomial transformation. Each point was labeled with the site name and age data. Samples from 2004 and 2011 were found to have inaccurate GPS measurements, and as a result are placed on the map manually using a combination of field maps, topographic maps, and site photographs. Their GPS coordinates listed in Table 1 reflect the rectified coordinates.

RESULTS

All surface samples represent exposed surface vegetation and were observed to be intact and rooted in their original growth orientation and location, which strongly suggests that their locations had not been altered by glacier advance (Gould et al., 2010). Samples at depth occur in fine-grained stratified sediment, indicating that their subsequent burial was due in part to flood events, rather than burial by glacial till.

Well-preserved plant samples that are exposed by modern glacial retreat provide strong evidence of continuous ice coverage at their location since the encapsulation of the plant by the advancing ice (Anderson et al., 2008). Therefore, the age of the sample indicates the time at which the ice reached the location of that sample, which remained glaciated until recently. Had the ice retreated from the plant site, the sample would be subject to the elements and would have decomposed. Older plants correspond with earlier capture by the advancing glacier, while younger plants are captures more recently. Table 1 contains information on all samples collected from 2004 to 2016.

Surface Samples

The preserved *in-situ* plant samples that were recovered are predominately from the surface. Figure 1 presents the geographic positions of all surface samples recovered by the Ice Core Paleoclimatology Research Group from 2004 to 2016. The samples were age dated, and the age (cal yr BP) and elevation (masl) data are presented alongside their geographic locations in Figures 2 and 3. The age data for the plants are provided in Table 1, along with the $\pm 1\sigma$ value in cal yr BP. When samples had multiple ages, the ages were averaged and mapped and these values are available in Table 2. The age and spatial data for the plants allow for the reconstruction of glacial advancement margins by correlating related points based upon age. Several observations can be made, based upon the age and elevation data; samples located further downslope from the modern glacial margin are younger in age, spatially close samples are of similar age, and within spatially close groups of samples, those at lower elevation are older.

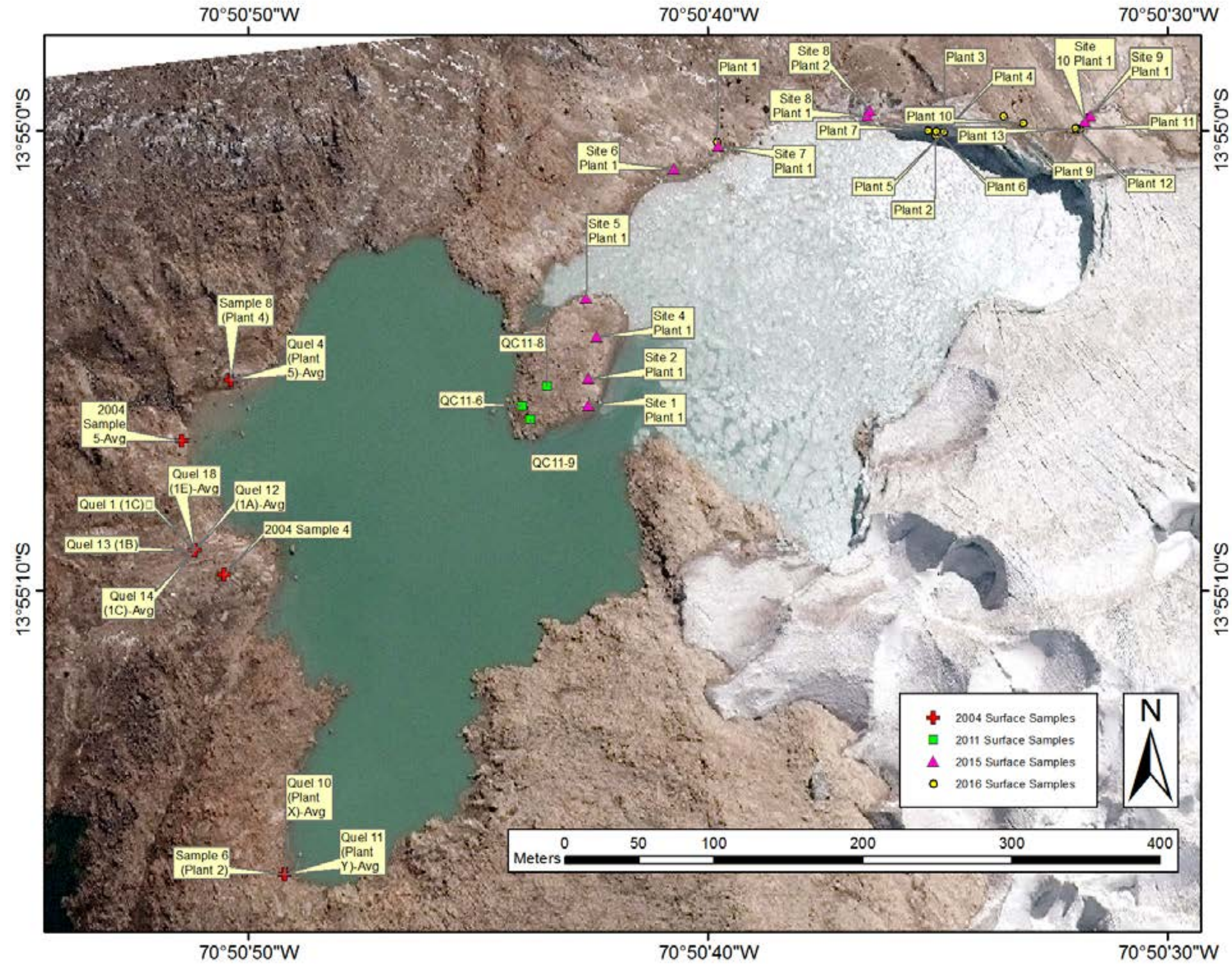

Figure 1: Locations of in-situ preserved plant samples collected from the surface, mapped onto satellite imagery of the North Lake Lobe of the QIC.

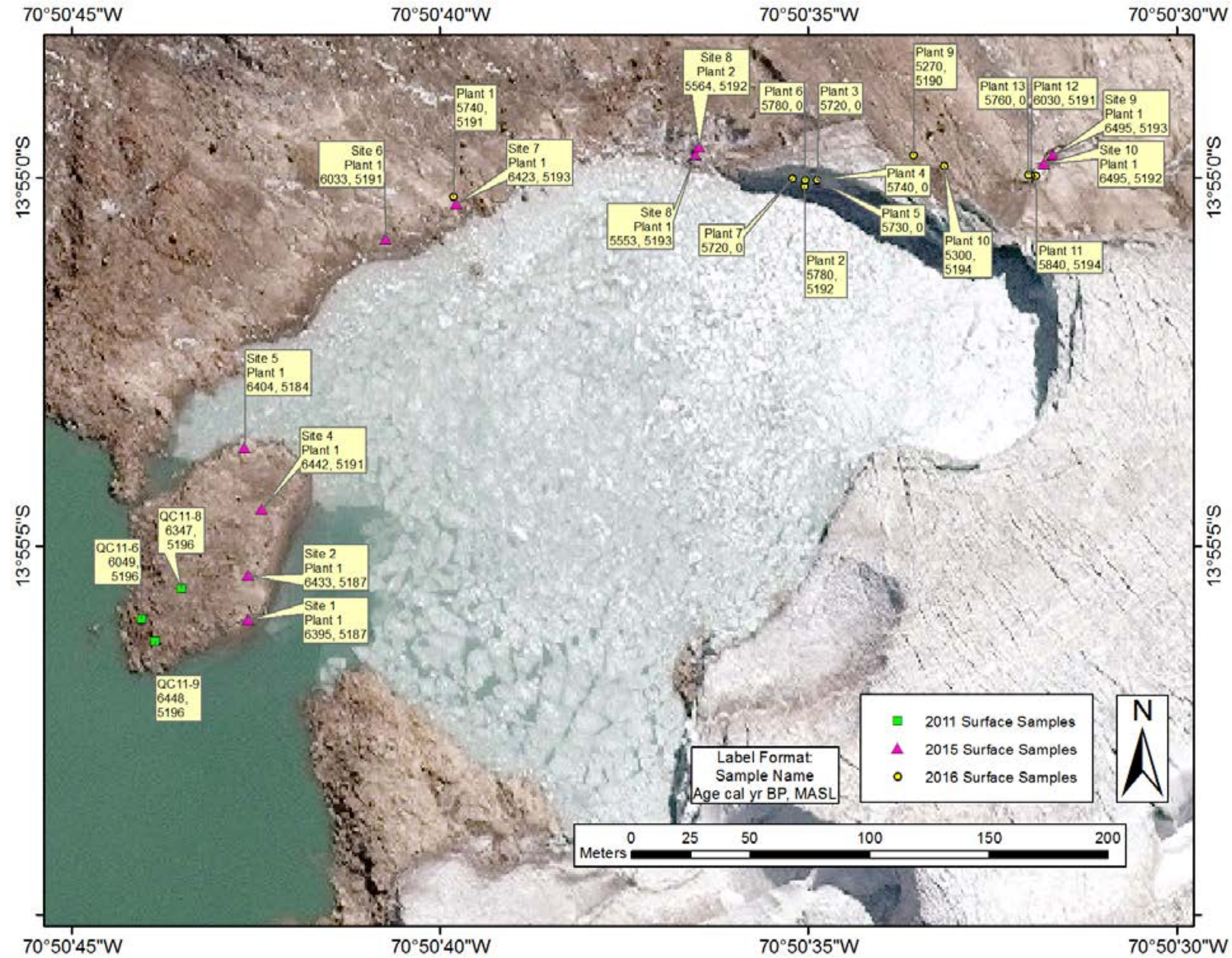

Figure 2: Surface in-situ preserved plant samples recovered in 2011, 2015, and 2016 from the island and north edge of the proglacial lake, mapped on satellite imagery of the North Lake Lobe of the QIC and labeled with their calculated calendar age and elevations in masl. Elevation values labeled "0" are representative of null values, or no data.

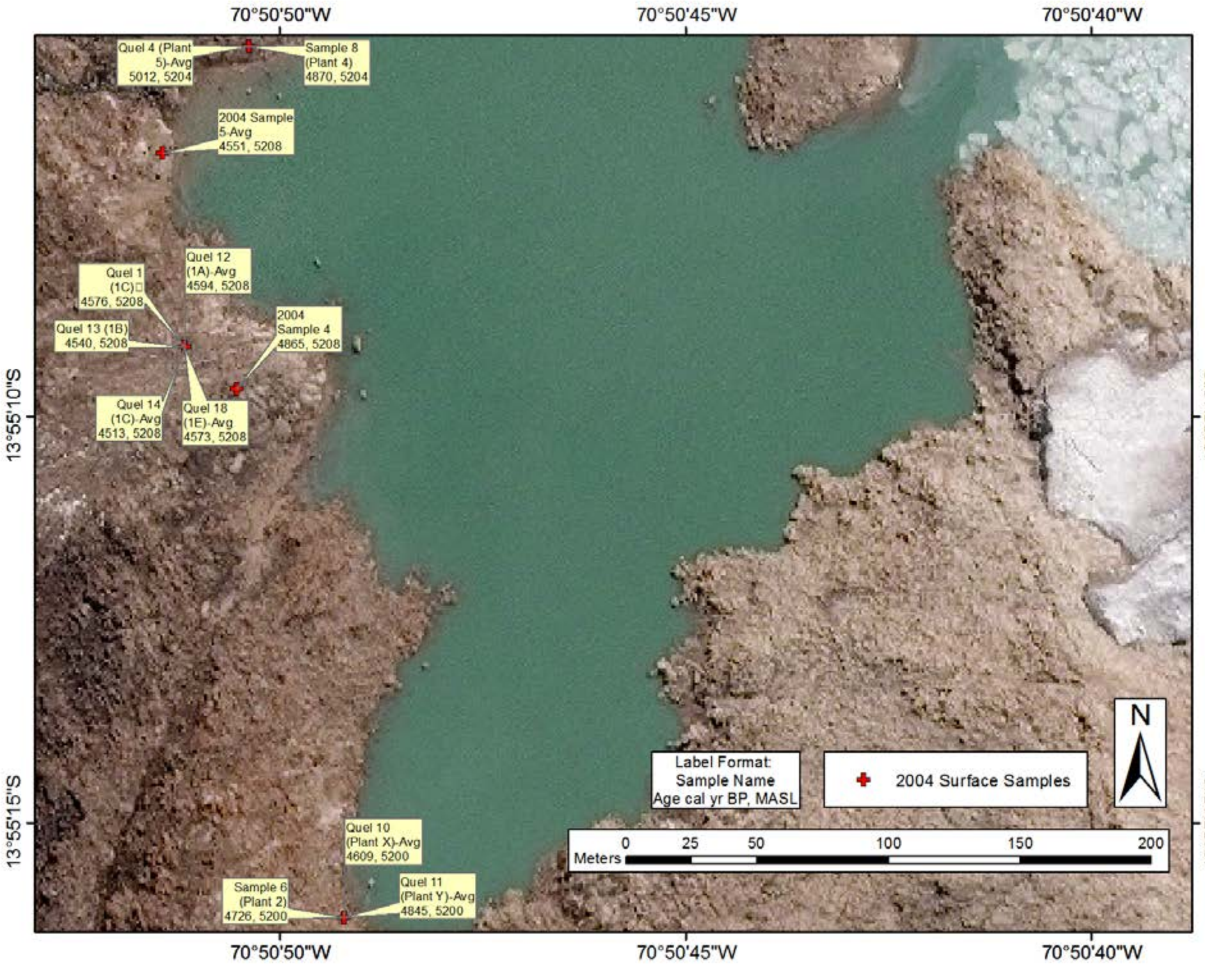

Figure 3: In-situ preserved plant samples recovered in 2004 from the west edge of the proglacial lake, mapped to satellite imagery of the North Lake Lobe of the QIC and labeled with their calculated calendar age and elevation in masl.

Depth Samples

Several subsurface samples were collected during the 2011 and 2015 field season. These samples were located on the island in the middle of the proglacial lake, approximately 150 m downslope of the retreating glacial lobe. These samples occurred in vertical alignment, sharing the same geographic coordinates as the uppermost surface sample. Figure 4 presents the 2011 and 2015 subsurface samples along with their age and depth data. Tables 3 and 4 present the vertical arrangement of these subsurface samples. Samples that occur at greater depth are older than those above, and any deviation from this sequence is due to the mean of the age range being presented. Age discrepancies can be resolved by utilizing the ±1σ value to examine the age range.

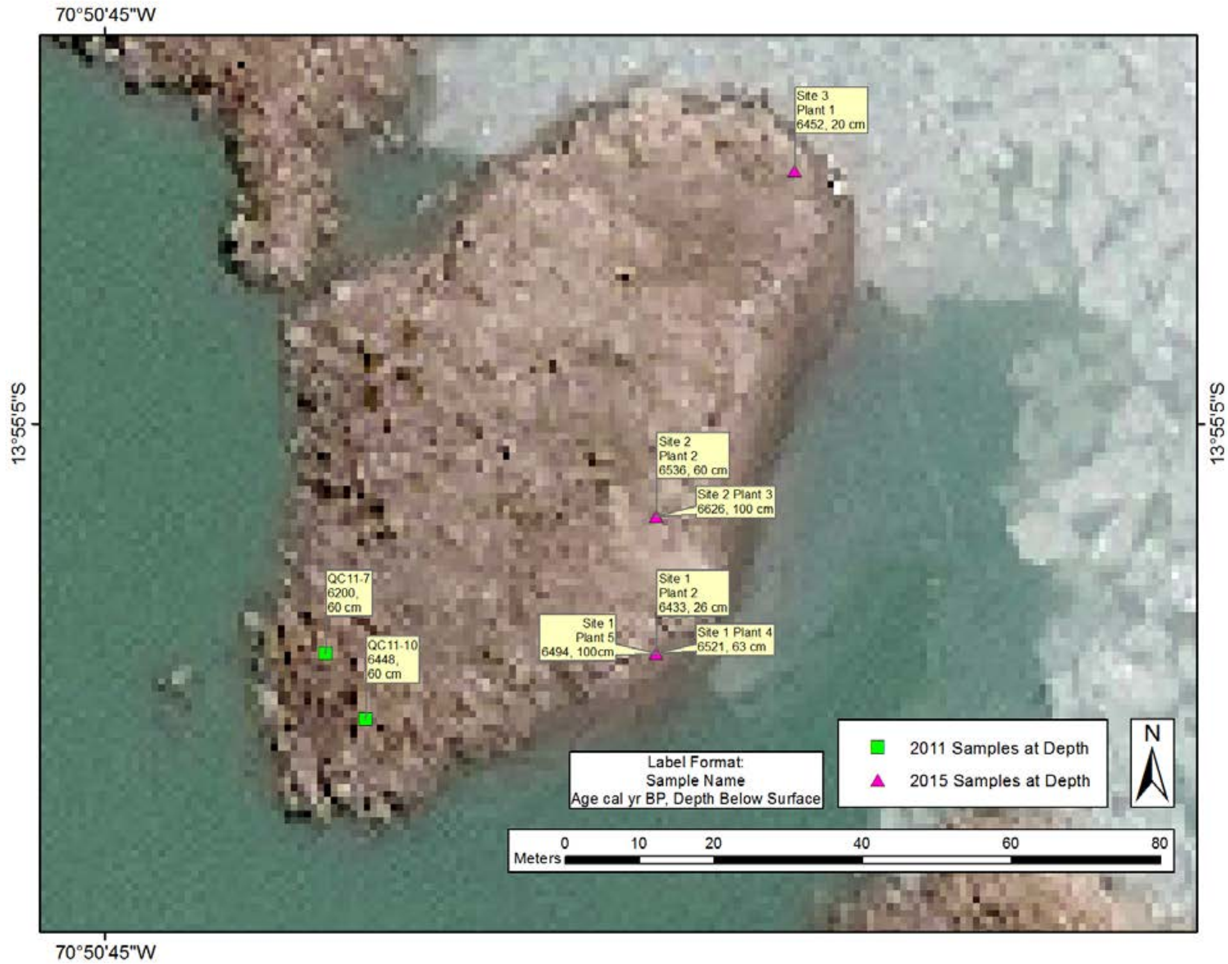

Figure 4: In-situ preserved plant samples recovered in 2011 and 2015 from the island located in the proglacial lake, mapped to satellite imagery of the North Lake Lobe of the QIC and labeled with their calculated calendar age and depth from surface in centimeters.

Year	Sample	Site	Age cal yr BP	±1σ cal yr BP	Latitude	Longitude	MASL	Depth
2004	2004 Sample 4	N/A	4865	28	-13.91935	-70.847369	5208	Surface
2004	2004 Sample 5	N/A	4463	23	-13.918544	-70.847624	5208	Surface
2004	2004 Sample 5-Run 1	N/A	4578	50	-13.918544	-70.847624	5208	Surface
2004	2004 Sample 5-Run 2	N/A	4613	40	-13.918544	-70.847624	5208	Surface
2004	Sample 8 (Plant 4)	N/A	4870	104	-13.918544	-70.847624	5204	Surface
2004	Quel 4 (Plant 5)-Run 1	N/A	5003	49	-13.918544	-70.847624	5204	Surface
2004	Quel 4 (Plant 5)-Run 2	N/A	5020	47	-13.918177	-70.847328	5204	Surface
2004	Quel 10 (Plant X)-Run 1	N/A	4606	39	-13.918177	-70.847328	5200	Surface
2004	Quel 10 (Plant X)-Run 2	N/A	4611	42	-13.918177	-70.847328	5200	Surface
2004	Quel 11 (Plant Y)-Run 1	N/A	4843	22	-13.918177	-70.847328	5200	Surface
2004	Quel 11 (Plant Y)-Run 2	N/A	4846	25	-13.921158	-70.847003	5200	Surface
2004	Sample 6 (Plant 2)	N/A	4726	36	-13.921158	-70.847003	5200	Surface
2004	Quel 12 (1A)-Run 1	N/A	4613	41	-13.921158	-70.847003	5208	Surface
2004	Quel 12 (1A)-Run 2	N/A	4575	53	-13.921158	-70.847003	5208	Surface
2004	Quel 13 (1B)	N/A	4540	41	-13.921158	-70.847003	5208	Surface
2004	Quel 1 (1C)	N/A	4576	52	-13.921158	-70.847003	5208	Surface
2004	Quel 14 (1C)-Run 1	N/A	4491	29	-13.921158	-70.847003	5208	Surface
2004	Quel 14 (1C)-Run 2	N/A	4534	36	-13.919205	-70.847549	5208	Surface
2004	Quel 18 (1E)-Run 1	N/A	4576	52	-13.919205	-70.847549	5208	Surface
2004	Quel 18 (1E)-Run 2	N/A	4569	53	-13.919205	-70.847549	5208	Surface
2011	QC11-6	N/A	6049	35	-13.918332	-70.845567	5196	Surface
2011	QC11-7	N/A	6200	35	-13.918332	-70.845567	5196	60 cm
2011	QC11-8	N/A	6347	40	-13.918203	-70.845426	5196	Surface
2011	QC11-9	N/A	6448	55	-13.918413	-70.845519	5196	Surface
2011	QC11-10	N/A	6448	40	-13.918413	-70.845519	5196	60 cm
2015	Plant 1	1	6395	28	-13.919205	-70.847549	5187	Surface
2015	Plant 2	1	6433	32	-13.919205	-70.847549	5187	26 cm
2015	Plant 3	1	N/A	N/A	-13.919205	-70.847549	5187	40 cm
2015	Plant 4	1	6521	40	-13.920358	-70.844533	5187	63 cm
2015	Plant 5	1	6494	27	-13.920358	-70.844533	5187	100 cm
2015	Plant 1	2	6433	32	-13.91815	-70.845117	5187	Surface
2015	Plant 2	2	6536	43	-13.91835	-70.845217	5187	60 cm
2015	Plant 3	2	6626	29	-13.91835	-70.845217	5187	100 cm
2015	Plant 1	3	6452	24	-13.918333	-70.845167	5186	20 cm
2015	Plant 1	4	6442	27	-13.918333	-70.845167	5191	Surface
2015	Plant 1	5	6404	27	-13.918333	-70.845167	5184	Surface
2015	Plant 1	6	6033	52	-13.918333	-70.845167	5191	Surface
2015	Plant 1	7	6423	26	-13.918333	-70.845167	5193	Surface
2015	Plant 1	8	5553	40	-13.918167	-70.845167	5193	Surface
2015	Plant 2	8	5564	38	-13.918167	-70.845167	5192	Surface
2015	Plant 1	9	6495	34	-13.918167	-70.845167	5193	Surface
2015	Plant 1	10	6495	34	-13.91775	-70.845	5192	Surface
2016	Plant 1	N/A	5740	30	-13.917917	-70.845117	5191	Surface
2016	Plant 2	N/A	5780	30	-13.917683	-70.845183	5192	Surface
2016	Plant 3	N/A	5720	25	-13.9169	-70.84465	N/A	Surface
2016	Plant 4	N/A	5740	30	-13.916767	-70.844383	N/A	Surface
2016	Plant 5	N/A	5730	25	-13.916583	-70.843483	N/A	Surface
2016	Plant 6	N/A	5780	30	-13.91655	-70.843467	N/A	Surface
2016	Plant 7	N/A	5720	25	-13.916583	-70.842133	N/A	Surface
2016	Plant 9	N/A	5270	25	-13.916617	-70.842167	5190	Surface
2016	Plant 10	N/A	5300	30	-13.916738	-70.844393	5194	Surface
2016	Plant 11	N/A	5840	30	-13.916698	-70.843072	5194	Surface
2016	Plant 12	N/A	6030	35	-13.916677	-70.843022	5191	Surface
2016	Plant 13	N/A	5760	30	-13.916677	-70.843022	N/A	Surface
2016	Plant 14	N/A	4590	25	-13.916677	-70.843022	5189	Surface

Table 1: Data for the preserved in-situ plant samples collected by members of the Ice Core Paleoclimatology Group from 2004-2016. The sample name, calculated age, standard deviation, coordinates, and elevation are presented.

Year	Sample	Age (cal yr BP)	Latitude	Longitude	Notes
2004	2004 Sample 5-CAMS Avg	4596	-13.918544	-70.847624	Mean calculated using CAMS Runs 1 and 2.
2004	2004 Sample 5-Avg	4551	-13.918544	-70.847624	Calculated using all CAMS/NOSAMS ages for 2004 Sample 5.
2004	Quel 4 (Plant 5)-Avg	5012	-13.918177	-70.847328	Mean calculated using Runs 1 and 2.
2004	Quel 10 (Plant X)-Avg	4609	-13.921158	-70.847003	Mean calculated using Runs 1 and 2.
2004	Quel 11 (Plant Y)-Avg	4845	-13.921158	-70.847003	Mean calculated using Runs 1 and 2.
2004	Quel 12 (1A)-Avg	4594	-13.919205	-70.847549	Mean calculated using Runs 1 and 2.
2004	Quel 14 (1C)-Avg	4513	-13.919205	-70.847549	Mean calculated using Runs 1 and 2.
2004	Quel 18 (1E)-Avg	4573	-13.919205	-70.847549	Mean calculated using Runs 1 and 2.

Table 2: Averaged sample age data obtained using samples with multiple age values from the 2004 field season.

Site 1	Age (cal yr BP)	Depth (cm)		Site 2	Age (cal yr BP)	Depth (cm)		Site 3	Age (cal yr BP)	Depth (cm)
Plant 1	6395±28	0		Plant 1	6433±32	0				
Plant 2	6433±32	26						Plant 1	6452±24	20
Plant 3	No Data	40								
Plant 4	6521±40	63		Plant 2	6536±43	60				
Plant 5	6494±27	100		Plant 3	6626±29	100				

Table 3: Depth relationship for 2015 preserved in-situ plant samples. All sites occur on the island within the proglacial lake (Figure 1), and have approximately equal surface elevations.

Sample	Age (cal yr BP)	Depth (cm)		Sample	Age (cal yr BP)	Depth (cm)
QC11-6	6049±35	0		QC11-9	6448±55	0
QC11-7	6200±35	60		QC11-10	6448±40	60

Table 4: Depth relationship for 2011 preserved in-situ plant samples. Samples QC11-6 and QC11-7 occur on the island within the proglacial lake (Figure 1), while QC11-9 and QC11-10 occur on the slope to the south of the lake.

Discussion

Due to two distinct features of the QIC, the behavior of the North Lake Lobe reflects the behavior of the ice cap as a whole. The first is that the North Lake Lobe is not a lower elevation outlet glacier with a large slope, but is part of the QIC itself. Second, the QIC is located on a large, flat plateau and its gentle topography results in the relatively flat nature of the QIC (Buffen et al., 2009). From the North Lake Lobe to the peak, the change in elevation is minor compared to most alpine glaciers. As a result, minor changes in the average elevation of the equilibrium line affect large swaths of the QIC, and any response seen at the North Lobe Lake likely will mirror the response of the QIC.

Analysis of the temporospatial relationships of the preserved *in-situ* plant samples has yielded several mapped glacial advancement margins (Figure 6). It is our conclusion that a plant's preservation, and consequently radiocarbon calculated age, coincide with contact with the advancing ice. Therefore, we are able to reconstruct the positions of several margins which represent a snapshot of the glacier's advancing face, with samples being preserved within $\pm 1\sigma$ of their calculated age at each extent. These separate temporal groupings were initially determined using the Jenks Natural Breaks Optimization algorithm, which separates the samples into a predetermined number of classes utilizing their calculated ages. This method minimizes the variance within each class and maximizes the variance between classes. However, a weakness of this method is that the desired number of class breaks is arbitrary, and must be chosen manually. Instead, class breaks were determined utilizing the Derivatives of Kernel Density Estimator (dkde) function of the CRAN R system for statistical computation. These breaks separate the plant samples into temporally significant groups (Figure 1, Table 1, Table 6).

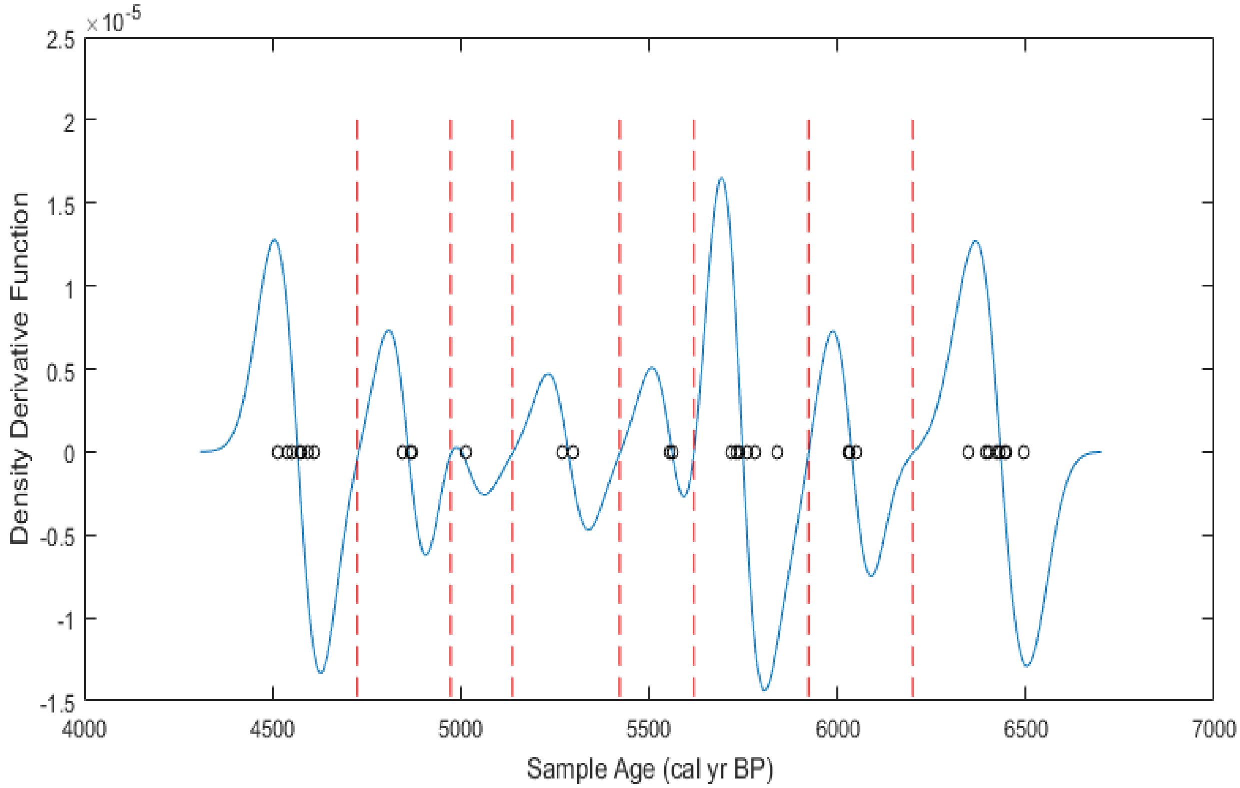

Figure 5: dkde analysis of the age data of surface plants recovered from the North Lake Lobe of the QIC. Local minima indicate the lowest probability of occurence of a data point, and are used to justify break points between temporally related data. Age data points are indicated by the hollow black circles. The dashed red lines indicate local relevant minima, which coincide to the break values.

Break 1	Break 2	Break 3	Break 4	Break 5	Break 6	Break 7
4724	4972	5136	5422	5618	5922	6198

Table 5: Local minima values in cal yr BP obtained from the dkde analysis of the surface plant sample ages recovered at the North Lake Lobe of the QIC. These values were used to define break points in the data set.

Year	Sample	Site	Cal. Age	Class Age Avg.	Class σ
2004	Quel 14 (1C)-Avg	N/A	4513	4565	30.4
2004	Quel 13 (1B)	N/A	4540		
2004	2004 Sample 5-Avg	N/A	4551		
2004	Quel 18 (1E)-Avg	N/A	4573		
2004	Quel 1 (1C)*	N/A	4576		
2004	Quel 12 (1A)-Avg	N/A	4594		
2004	Quel 10 (Plant X)-Avg	N/A	4609		
2004	Quel 11 (Plant Y)-Avg	N/A	4845	4898	66.5
2004	2004 Sample 4	N/A	4865		
2004	Sample 8 (Plant 4)	N/A	4870		
2016	Plant 9	N/A	5270	5285	15
2016	Plant 10	N/A	5300		
2015	Plant 1	8	5553	5558	5.5
2015	Plant 2	8	5564		
2016	Plant 3	N/A	5720	5756	36.5
2016	Plant 7	N/A	5720		
2016	Plant 5	N/A	5730		
2016	Plant 1	N/A	5740		
2016	Plant 4	N/A	5740		
2016	Plant 13	N/A	5760		
2016	Plant 2	N/A	5780		
2016	Plant 6	N/A	5780		
2016	Plant 11	N/A	5840		
2016	Plant 12	N/A	6030	6037	8.3
2015	Plant 1	6	6033		
2011	QC11-6	N/A	6049		
2011	QC11-8	N/A	6347	6431	44.4
2015	Plant 1	1	6395		
2015	Plant 1	5	6404		
2015	Plant 1	7	6423		
2015	Plant 1	2	6433		
2015	Plant 1	4	6442		
2011	QC11-9	N/A	6448		
2015	Plant 1	9	6495		
2015	Plant 1	10	6495		

Table 6: Surface plant samples from the North Lake Lobe of the QIC sorted into temporally significant classes utilizing the break values obtained with the dkde function.

Within each margin, zones of high confidence represent a glacial extent that was estimated using temporo-spatial data from the plant samples, and the topography of the plateau. Zones of low/no confidence are not corroborated by plant samples, and represent estimations based on elevation relying on the notion that the glacier did not retreat beyond any of the preserved *in-situ* samples until the last decade and that glacial ice flows downhill.

Overall, the ice margins indicated by plant samples indicate a net advancement of the QIC from approximately 6,431 cal yr BP to 4,565 cal yr BP. Due to the presence of the marginal proglacial lake at the North Lake Lobe, no plant samples that were preserved in the basin were recovered. Even if recovery were possible, the samples would likely have degraded such that they would be useless for age dating. As a result of this apparent gap of samples in the downslope direction, the rates of advancement between the margins that are located between the two high-confidence end members cannot be calculated with a reasonable degree of accuracy. Samples recovered from the island and western shoreline represent the only high-confidence sections where a rate of advancement can be calculated. From the oldest high-confidence margin at ~6,431 cal yr BP to the youngest high-confidence margin at ~4,565 cal yr BP, the ice advanced 288.9 m downslope. Utilizing the downslope distance between the ice margins and the calculated ages of those margins, we determined the lower limit of the average rate of advancement to be 0.15 m per year. While this metric is useful for analyzing net behavior of the lobe, caution must be taken not to consider it as an indicator of specific behavior. Although the glacier was located at margin A at time t_0, and then was located some distance downslope at margin B at time t_1, we only know these end members and therefore the net result, but not the glacier's behavior between them. It is likely that the glacier did not advance at a uniform rate or even advance downslope at all times. Retreat could have occurred between these margins, bounded by the upslope samples that had not been exposed until recent decades. While these margins can provide some insight into the long-term behavior of the North Lake Lobe, the uneven spatial distribution of plant material results in large gaps of low confidence. Furthermore, a lack of a detailed digital elevation model precludes accurate modeling of the low-confidence areas using contours of equal elevation.

In addition to these samples as indicators of past ice margins, there are other scenarios that might explain these data. These plants could indicate either rising or lowering lake still stands, but several major obstacles stand in the way of this conclusion. First, the Lower North Lake's water level is controlled by a bedrock outflow at its northeastern edge. Second, there are issues with preservation due to lake level still stands. If the samples indicate still stands of a lowering lake, ^{14}C analysis of the plant samples should yield younger ages as elevation lowers. This is not the trend seen at the North Lake Lobe (Figures 2 and 3). Conversely, if the samples indicate still stands of a rising lake, the plant samples should yield younger ages with increased elevation, which is demonstrated by the surface samples of the Lower North Lake. However, any samples below the water level would decompose prior to being frozen in advancing ice. These surface samples are also not covered in sediment, which is not indicative of residence within the lake basin. Another possible explanation for the preservation of these samples is a single snowfall event blanketing the area, preserving all the samples at once. However, if the snow remained until the ice advanced over the samples, this would not account for the large range seen in the calculated age data.

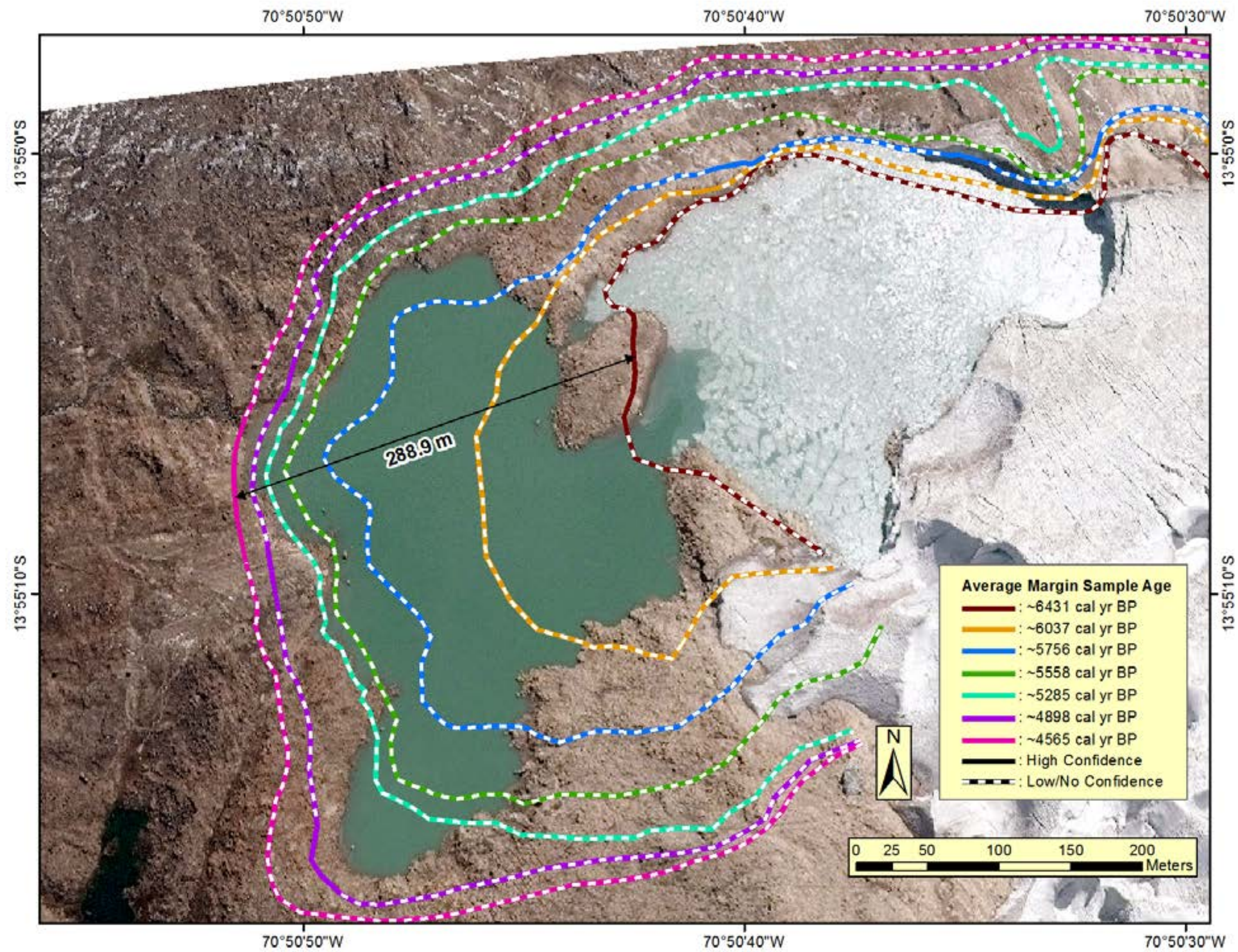

Figure 6: Past ice margins of the North Lake Lobe of the Quelccaya Ice Cap, Peru, as evidenced by preserved in-situ plant samples and elevation data. Only surface samples are utilized (see Table 1 for the samples used in this analysis). Sections of high confidence were determined by the similar temporal and spatial relationships of multiple plant samples. Sections of low/no confidence were inferred from topographic data. The transect is a measure of the downslope distance from the oldest plant margin at ~6431 cal yr BP, and the youngest plant margin at ~4565 cal yr BP.

Analyses of the samples at depth reveal a highly dynamic environment. Due to the fine-grained nature of the sediments that compose the lake shore, this deposited material was unlikely to be glacial till. Instead, the burial of these plants by fine-grained material indicates the occurrence of high discharge events. To the north of the North Lake Lobe are the remnants of a second proglacial lake, designated Upper North Lake. The Upper North Lake has a bed elevation at 5191 masl, and is flanked by rising slopes on its north, west, and east sides. The south side is punctuated by a central ridge feature. The basin is filled with fine-grained sediment, and crosscut by modern drainage channels. Prior to the glacial advancement at ~6431 cal yr BP, the southern side of the Upper North Lake basin was dammed by ice (Figure 7). Over time, the Upper North Lake filled with sediment and water. Eventually, the water either melted through the ice dam or floated it, resulting in a massive discharge of water and sediment into the Lower North Lake which buried the plants *in-situ*. These sediments would then provide a new growth medium for the plants after the water subsided. The depth record indicates a succession of these flooding events occurring from ~6,630 cal yr BP to ~6450 cal yr BP, prior to the glacial advancement that preserved the samples on the island.

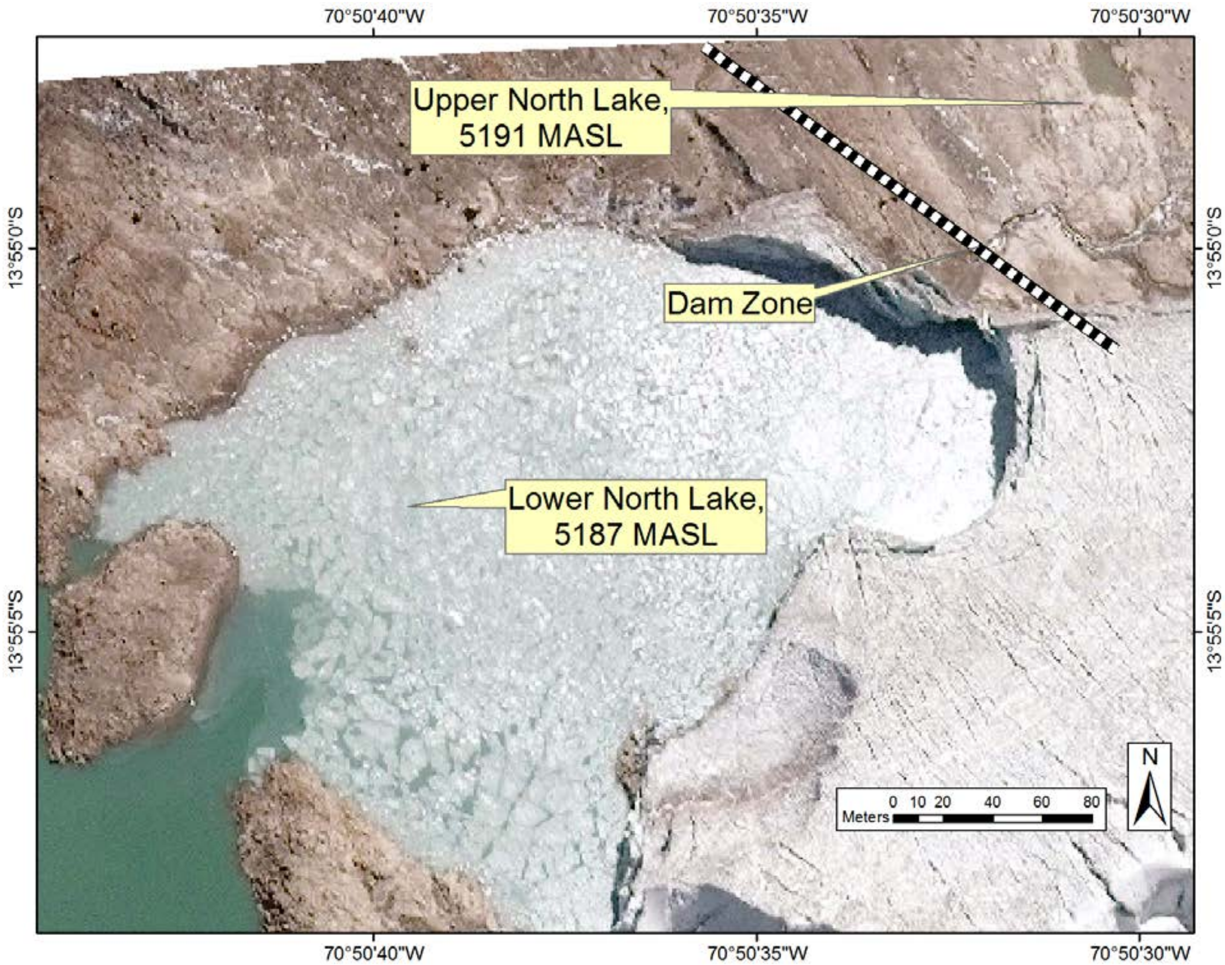

Figure 7: Map indicating the relative locations of the Upper and Lower North Lakes, and the zone between them where ice formed a dam, resulting in later flooding of the Lower North Lake, and the burial of plants by sediment near the Lower North Lake.

Placing this behavior into a regional perspective, we are able to correlate the advancing ice with changing climatic conditions on the Altiplano by utilizing ice core records recovered from Huascarán, a high altitude tropical glacier located ~880km northeast of Quelccaya. While the ice core record of the QIC only goes back to 1800 cal yr BP due to pressure melting at the base, the record from Huascarán provides nearly 20,000 years of climate history. After the Last Glacial Maximum, the $\delta^{18}O$ values began to rise, indicative of warming regional temperatures (Figure 2) (Thompson et al., 1995), and peaks at approximately 8,500 cal yr BP. From ~8,500 cal yr BP to ~250 cal yr BP, the snowfall became more isotopically depleted (lower $\delta^{18}O$), indicative of regional climatic cooling. During the same period, the 100-year averages of dust concentrations were elevated, indicative of drier conditions (Thompson et al., 1995). In spite of decreased regional precipitation over several centuries, the North Lake Lobe, and by extension, the QIC, gained mass and advanced. We conclude that the QIC responds much more readily to changes in air temperature than to changes in precipitation rate. This coincides with the findings of Malone et al. (2015), who utilized climate reconstruction models to conclude that temperature is the primary control on area changes of low-latitude glaciers.

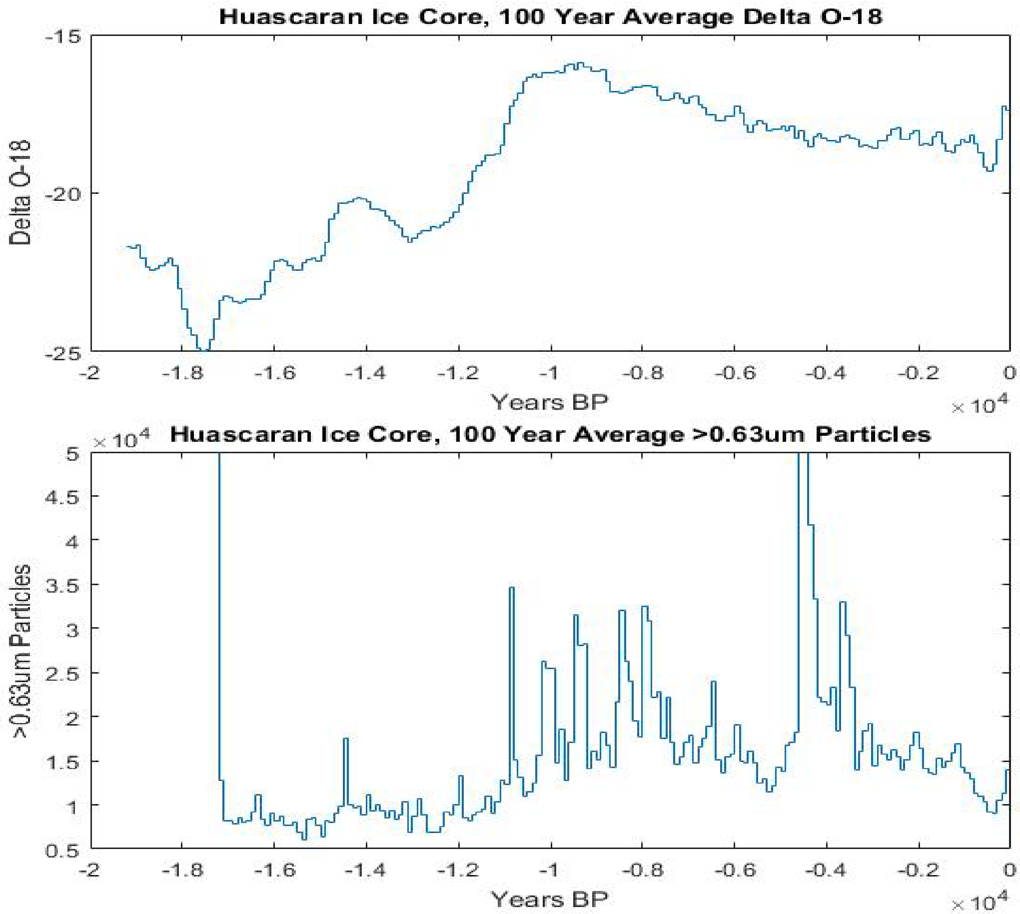

Figure 8: 100-year average $\delta^{18}O$ and dust concentrations from the Huascarán ice core 2 (Thompson et al., 1995). $\delta^{18}O$ rises until ~10,000 cal yr BP, indicating the mid-Holocene thermal maximum. From ~10,000 cal yr BP to ~500 cal yr BP, the $\delta^{18}O$ decreases, indicative of regional cooling. The same period is punctuated by sharp spikes in dust concentrations, indicative of prolonged drier conditions. The QIC advanced during this mid-Holocene cooling event, in spite of these drier conditions.

The Mid-Holocene cooling event that brought about the advancement of the QIC is not a singular, regional phenomenon. Across several continents, evidence can be found of advancing glacial ice or climatic cooling. Ice core records recovered from Mt. Kilimanjaro in Kenya indicate that there was significant cooling during the same period as indicated by Huascarán, approximately 6,000 cal yr BP (Thompson et al., 2002). In the Italian Alps of Europe, glacial ice advancement buried the body of a man known as "Ötzi", or the Tyrolean Iceman, whose remains were preserved in advancing glacial ice nearly 5,300 cal yr BP (Kutschera and Müller, 2003). In the East China Sea, sediment cores reveal a major decrease in sea surface temperature from 5,600 cal yr BP to 4,000 cal yr BP (Zhao et al., 2014). Wanner et al. (2014) conducted a data based review of 23 temperature time series through the Holocene, which indicated negative temperature trends globally, most prominently in the Northern Hemisphere, during the mid-Holocene. Considered together, these records indicate that climatic cooling occurred in both hemispheres and in several different environments during the mid-Holocene, which is indicative of a global cooling event. Magny and Haas (2004) explored this abrupt cooling event further, analyzing 44 climatic signals from the mid-Holocene which indicated the global ubiquity of the cooling trend. They found that the rapid onset of the cooling event which allowed for the QIC to advance was due in part to several non-exclusive factors, namely insolation variation, orbital forcing, and ocean circulation instability prior to ~5600 years BP. However, our findings indicate that cooler conditions at the QIC were present nearly 1000 years prior to the climate reversal indicated by Magny and Haas (2004). Due to the persistence of cooler conditions at the QIC until recently, the mechanisms driving this abrupt cooling event could conceivably be associated with long term trends rather than oscillations associated with the unstable conditions during the mid-Holocene. It is possible that this global cooling trend has since been overridden by anthropogenic sources.

The rapid retreat of the North Lake Lobe of the QIC is alarming, as the current extent of the ice cap is smaller than it has been in the last 6,600 years or more. While the advancement of the North Lake Lobe required over 1,600 years to advance ~300 m, the retreat over the same distance has occurred within three decades and is accelerating (Thompson et al., 2013). This retreat indicates that current climatic conditions are staggeringly worse for the health of the QIC than in the last ~6,400 years, and such a retreat has not occurred in the last 6,600 cal yr BP. Furthermore, it affirms the findings of Thompson et al. (2013) which indicated the extreme sensitivity of low-latitude glaciers to climate change.

CONCLUSIONS

- Due to the topography and characteristics of the QIC, any behaviors that occur in the North Lake Lobe are reflected in the behavior of the QIC as whole.
- Preserved *in-situ* plant samples can be utilized to reconstruct past glacial advancement margins with varying degrees of confidence. Areas of high confidence occur where plant samples are spatially abundant and of similar age. As a result of the uneven spatial distribution of the collected preserved plant material, there are large areas of low/no confidence.
- Past ice margins derived from preserved *in-situ* plant samples can be used to demonstrate net behavior of the lobe and locations where the lobe did not retreat until recent decades.
- Preserved *in-situ* plant samples do not demonstrate behavior that occurred between the margins.
- Preserved *in-situ* plant samples found at depth strongly indicate successive flood events in the North Lake Valley caused by ice damming of the Upper North Lake, and subsequent raising of the water level and eventual floating of the ice. The result was mass movement of sediment and water into the Lower North Lake, successively burying plant samples *in-situ* until the glacial advancement at ~6431 cal yr BP.
- The North Lake Lobe and by extension the QIC advanced consistently between ~6,431 cal yr BP and ~4,565 cal yr BP.
- The North Lake Lobe advanced 290 m downslope over ~1,866 years, with the lower limit of the average rate of advancement being ~0.15 m per year.
- The advancement behavior of the QIC was driven primarily by climatic lowering of regional air temperature, as inferred by the climate record from the Huascarán ice core (Thompson et al., 1995).
- There is strong evidence that indicates a global cooling event during the mid-Holocene;
    1. The Quelccaya Ice Cap advancement
    2. Huascarán ice core record (Thompson et al., 1995)
    3. Kilimanjaro ice core record (Thompson et al., 2002)
    4. Preservation of Ötzi, the Tyrolean Iceman (Kutschera and Müller, 2003).
    5. Sediment cores of the East China Sea (Zhao et al., 2014)
    6. Data-based review of 23 Holocene temperature time series (Wanner et al., 2014).
    7. Holocene global cooling event (Magny and Haas, 2004).
- Recent climate warming and its effect on the QIC is unprecedented, and indicates that climatic conditions during the Mid-Holocene Thermal Maximum were not so detrimental to glaciers as they are today. The rate at which the QIC is retreating is especially alarming considering that the ice extent has not been smaller than it is now in the last ~6,500 cal yr BP or more.

RECOMMENDATIONS FOR FUTURE WORK

As the North Lake Lobe retreats, more plant samples may be exposed for possible collection and age dating. As more samples are mapped, a more accurate picture of the QIC's behavior will be available. If plants that are discovered upslope are age dated greater than ~10,000 years old, this would indicate that the QIC existed before the mid-Holocene thermal maximum, allowing us to assess this with respect to modern retreat behavior. Future sediment analysis of the lakeshore deposits where samples were found preserved at depth would be of intense interest, as it would help determine the process by which these plants were buried. This would allow for a more thorough understanding of the behavior of the North Lake.

If a digital elevation model of the North Lake Lobe basin is constructed, it may be possible to more accurately map ice margins in the areas of low confidence and even model the extent of the glacial ice. If volumetric data are made available by modeling the lobe at different margins, it would be possible to analyze the ice cap's accumulation rate at previous margins. From here, one could explore the sensitivity of the QIC to drought conditions observed during the mid-Holocene.

Furthermore, the very existence of these preserved plant samples requires closer examination. This is one of the few known sites in the world where plants are preserved intact beneath an ice cap. Determination of the ice and soil mechanics that allowed these plants to remain unharmed is of intense interest and would provide insight into the ice flow at the base of an ice cap.

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APPENDICES

Sample data

Year	Sample	Site	Age cal yr BP	±1σ cal yr BP	Latitude	Longitude	MASL	Depth
2004	2004 Sample 4	N/A	4865	28	-13.91935	-70.847369	5208	Surface
2004	2004 Sample 5	N/A	4463	23	-13.918544	-70.847624	5208	Surface
2004	2004 Sample 5-Run 1	N/A	4578	50	-13.918544	-70.847624	5208	Surface
2004	2004 Sample 5-Run 2	N/A	4613	40	-13.918544	-70.847624	5208	Surface
2004	Sample 8 (Plant 4)	N/A	4870	104	-13.918544	-70.847624	5204	Surface
2004	Quel 4 (Plant 5)-Run 1	N/A	5003	49	-13.918544	-70.847624	5204	Surface
2004	Quel 4 (Plant 5)-Run 2	N/A	5020	47	-13.918177	-70.847328	5204	Surface
2004	Quel 10 (Plant X)-Run 1	N/A	4606	39	-13.918177	-70.847328	5200	Surface
2004	Quel 10 (Plant X)-Run 2	N/A	4611	42	-13.918177	-70.847328	5200	Surface
2004	Quel 11 (Plant Y)-Run 1	N/A	4843	22	-13.918177	-70.847328	5200	Surface
2004	Quel 11 (Plant Y)-Run 2	N/A	4846	25	-13.921158	-70.847003	5200	Surface
2004	Sample 6 (Plant 2)	N/A	4726	36	-13.921158	-70.847003	5200	Surface
2004	Quel 12 (1A)-Run 1	N/A	4613	41	-13.921158	-70.847003	5208	Surface
2004	Quel 12 (1A)-Run 2	N/A	4575	53	-13.921158	-70.847003	5208	Surface
2004	Quel 13 (1B)	N/A	4540	41	-13.921158	-70.847003	5208	Surface
2004	Quel 1 (1C)	N/A	4576	52	-13.921158	-70.847003	5208	Surface
2004	Quel 14 (1C)-Run 1	N/A	4491	29	-13.921158	-70.847003	5208	Surface
2004	Quel 14 (1C)-Run 2	N/A	4534	36	-13.919205	-70.847549	5208	Surface
2004	Quel 18 (1E)-Run 1	N/A	4576	52	-13.919205	-70.847549	5208	Surface
2004	Quel 18 (1E)-Run 2	N/A	4569	53	-13.919205	-70.847549	5208	Surface
2011	QC11-6	N/A	6049	35	-13.918332	-70.845567	5196	Surface
2011	QC11-7	N/A	6200	35	-13.918332	-70.845567	5196	60 cm
2011	QC11-8	N/A	6347	40	-13.918203	-70.845426	5196	Surface
2011	QC11-9	N/A	6448	55	-13.918413	-70.845519	5196	Surface
2011	QC11-10	N/A	6448	40	-13.918413	-70.845519	5196	60 cm
2015	Plant 1	1	6395	28	-13.919205	-70.847549	5187	Surface
2015	Plant 2	1	6433	32	-13.919205	-70.847549	5187	26 cm
2015	Plant 3	1	N/A	N/A	-13.919205	-70.847549	5187	40 cm
2015	Plant 4	1	6521	40	-13.920358	-70.844533	5187	63 cm
2015	Plant 5	1	6494	27	-13.920358	-70.844533	5187	100 cm
2015	Plant 1	2	6433	32	-13.91815	-70.845117	5187	Surface
2015	Plant 2	2	6536	43	-13.91835	-70.845217	5187	60 cm
2015	Plant 3	2	6626	29	-13.91835	-70.845217	5187	100 cm
2015	Plant 1	3	6452	24	-13.918333	-70.845167	5186	20 cm
2015	Plant 1	4	6442	27	-13.918333	-70.845167	5191	Surface
2015	Plant 1	5	6404	27	-13.918333	-70.845167	5184	Surface
2015	Plant 1	6	6033	52	-13.918333	-70.845167	5191	Surface
2015	Plant 1	7	6423	26	-13.918333	-70.845167	5193	Surface
2015	Plant 1	8	5553	40	-13.918167	-70.845167	5193	Surface
2015	Plant 2	8	5564	38	-13.918167	-70.845167	5192	Surface
2015	Plant 1	9	6495	34	-13.918167	-70.845167	5193	Surface
2015	Plant 1	10	6495	34	-13.91775	-70.845	5192	Surface
2016	Plant 1	N/A	5740	30	-13.917917	-70.845117	5191	Surface
2016	Plant 2	N/A	5780	30	-13.917683	-70.845183	5192	Surface
2016	Plant 3	N/A	5720	25	-13.9169	-70.84465	N/A	Surface
2016	Plant 4	N/A	5740	30	-13.916767	-70.844383	N/A	Surface
2016	Plant 5	N/A	5730	25	-13.916583	-70.843483	N/A	Surface
2016	Plant 6	N/A	5780	30	-13.91655	-70.843467	N/A	Surface
2016	Plant 7	N/A	5720	25	-13.916583	-70.842133	N/A	Surface
2016	Plant 9	N/A	5270	25	-13.916617	-70.842167	5190	Surface
2016	Plant 10	N/A	5300	30	-13.916738	-70.844393	5194	Surface
2016	Plant 11	N/A	5840	30	-13.916698	-70.843072	5194	Surface
2016	Plant 12	N/A	6030	35	-13.916677	-70.843022	5191	Surface
2016	Plant 13	N/A	5760	30	-13.916677	-70.843022	N/A	Surface
2016	Plant 14	N/A	4590	25	-13.916677	-70.843022	5189	Surface

Derivatives of kernel density estimator function

See page 9 of the kedd package from CRAN R at the following URL for function notation and further references.

Guidoum, Arsalane C. Kernel Estimator and Bandwidth Selection for Density and Its Derivatives. (2015): n. pag. Package 'kedd'. CRAN R, 2015. Web. 2 Mar. 2017. <https://cran.r-project.org/web/packages/kedd/kedd.pdf>.

Relevant local minima Script, dkde

```
#!/usr/bin/env Rscript
library(kedd)

localMinima <- function(arr) {
  ret <- c()
  for (i in 2:length(arr)-1) {
    if (arr[i] <= 0.0 & arr[i+1] > 0.0) {
      ret <- c(ret, i)
    }
  }
  ret
}

breakPoints <- function(arr) {
  d <- dkde(arr, deriv.order=1)
  plot(d)

  minima <- localMinima(d$est.fx)
  unlist(lapply(minima, function(idx) d$eval.points[idx]))
}

data <- scan("data.txt")
cat(paste(c(breakPoints(data), ""), collapse="\n"))
```

Derivatives of Kernel Density Estimator Calculated Break Values

Break 1	Break 2	Break 3	Break 4	Break 5	Break 6	Break 7
4724	4972	5136	5422	5618	5922	6198